Microwave Structural Health Monitoring Sensor for Deformation Measurement of Bended Steel Structures: Influence of Curvature Effect

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Abstract. *In this paper the utilization of microstrip antenna sensor for deformation monitoring in bended steel structures is presented. This kind of sensing element can be used in structural health monitoring systems. Deformation measurement by patch sensor is based on the reflection coefficient* S_{11} *investigation. So far, relationship between resonant frequency and change of patch dimensions was considered in literature only for planar microstrip sensors. In case of samples subjected to bending process the sensor geometry became non-planar. This fact affects measured resonant frequency, thus it should be studied. In order to analyze influence of patch sensor curvature on resonant frequency during bending process Finite Element Method (FEM) simulations were carried out. Results of analysis were experimentally verified.*

Keywords

Microstrip antenna sensor, nondestructive testing, deformation measurement, structural health monitoring, microwave technique

1. Introduction

In order to assure the safety of ships, aircrafts or civil structures various nondestructive testing (NDT) techniques are utilized. Nowadays periodic NDT inspection is often displaced or supported by Structural Health Monitoring (SHM). This trend is caused by complicated procedures of traditional inspections and high cost of maintenance. In case of some aspects SHM can be more effective than periodical inspection because it enables to oversee the state of structures in real time. Additionally, a good designed SHM system may check and inform about state of structure after extreme weather anomalies e.g. earthquake, hurricane or heavy snowfall [1–3]. SHM technique utilized in aircrafts provides the high level of safety, decreases the cost of maintenance and reduces the service time [4]. Typical systems consist of sensors, central data repository and a set of algorithms which allow to detect, localize, identify and predict potential damage. The information from sensors is usually sent by cables to data acquisition system. It increases the cost of installation and maintenance [5–7]. In case of large buildings such as bridges, the cost of additional cable installation is high. Moreover, because of the spread character of this sensor network, its conservation and service can be more problematic. Besides, there is an additional element, which can be damaged. Therefore, SHM systems are mainly applied in new civil structures. The cheap and wireless sensor networks will enable application of monitoring systems even in case of old structures. In this paper, the proposed deformation sensor was utilized for the evaluation of bended St3s steel sample (Poland). This type of steel is no longer utilized in new projects, but still many older constructions made of St3s are in service.

We may split SHM methods into two groups – global and local ones. The global SHM systems are based on visual inspection, infrared thermography, ultrasonics or acoustics. Nevertheless, for many large systems, global monitoring is impractical because of the lack of sensitivity of global features regarding local damages [8], [9]. For this reason in case of big structures local methods of damage detection should be utilized. They allow to check critical points of construction. In SHM technique many type of sensors are used such as resistive and capacitive strain gauges and fiber optic sensors [10].

The utilization of microstrip antenna sensors to stress/deformation evaluation or crack growth measurement became an object of interest of many researchers in the last few years [10–27]. Both mentioned applications rely on the reflection coefficient S_{11} study. In case of deformation measurement the strong relationship between resonant frequency f_r of microstrip sensor and patch resonator dimensions was utilized. In case of the second application, a crack in the ground plane will force the current to flow around it. As a result, the effective electrical length of the patch antenna increases, which shifts the antenna resonant frequency to a lower value.

Up to now, microstrip sensors with various shapes of

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patches were used for strain investigation. In case of in-plane tension subjected structures only rectangular patch sensors were utilized [13], [19], [21], [22], [25]. Deformation of bended elements was evaluated by rectangular [11], [27], circular [10], [17], [18], [20] and other shape of patch [15], [16] microstrip sensors. However, the influence of curvature effect on resonant frequency in these cases was not considered. In this paper considerable influence of curvature of rectangular patch on resonant frequency was noticed. This effect was described in details by Kin-Lu Wong for structures utilized in telecommunication [28], but in our case the resonant frequency is dependent on both: the change of the patch dimensions and curvature effect. Thus, an experiment and numerical analysis (in which deformation was evaluated by patch sensor) were carried out. Moreover the influence of curvature effect on resonant frequency for the designed sensor was determined.

2. Sensor Design

Microstrip antennas, filters and transmissions lines can be fabricated in printed circuit board (PCB) technology. They consist of a microstrip structure separated from a ground plane by a dielectric material [29–32]. In this paper a microstrip antenna sensor fed by a microstrip line is designed, as shown in Fig. 1. This way of feed is easy to fabricate and integrate with electronics.

At first the transmission-line model was utilized to design a microstrip antenna sensor and the correctness was validated by FEM analysis. Antenna sensors were developed on the double-side polymer laminate of thickness 0.5 mm (relative permittivity of 4.5). The patch, microstrip line and ground are made of copper (layer thickness of 35 µm). Patch sensor was designed for operation frequency of 12 GHz at the fundamental mode [29]. The results of calculation obtained by transmission-line model are presented in Tab. 1, whereas dimensions of the designed microstrip SHM sensor are shown in Fig. 2.

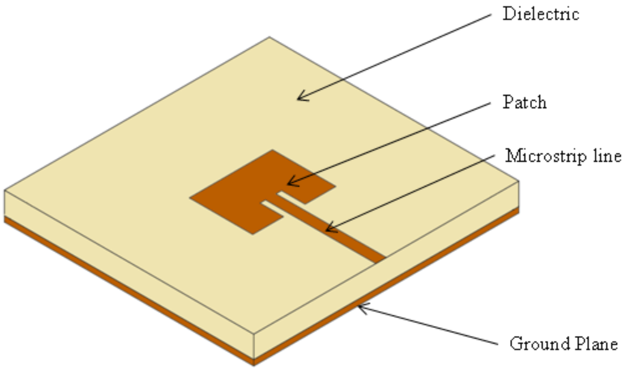

Fig. 1. Microstrip sensor fed by microstrip line.

Designed parameter name	Parameter value
W	7.538 mm
$\varepsilon_{\mathrm{reff}}$	4.056
ΔL	0.228 mm
L	5.75 mm
y_0	2.136 mm

Tab. 1. Results of transmission line model calculations [20].

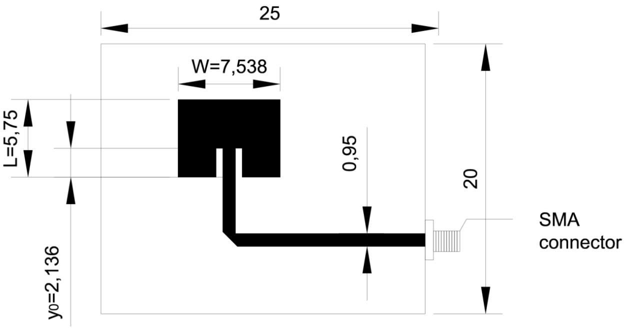

Fig. 2. View and dimensions (in mm) of the designed sensor [20].

3. Experimental Setup

In this article the utilization of microstrip antenna to evaluation of deformation in bended steel elements was studied. The scheme of experiment is shown in Fig. 3. One side of planar steel sample (beam sample) was fixed to static holding element and the opposite side was loaded using a set of weights in order to obtain various deformation levels. The top surface of sample was extended, whereas the bottom was shortened with increasing of load. For this reason, the investigated sensors were adhesively connected to both sides of beam sample, which was made of St3s construction steel – in accordance with Polish standards PN-88 H-84020 (an equivalent for S235JRG2 in European standards EN 10025). The parameters of St3s steel are presented in Tab. 2. The maximum value of load equals 0.9 kg for considered sample (within elastic range of the material stress-strain relationship).

Both transducers were placed in the same distance from loading force on opposite sides of sample in order to obtain the same strain level. Displacement u_y along the sample is presented in Fig. 4. The proposed placement of the transducers cannot be determined just by y-component

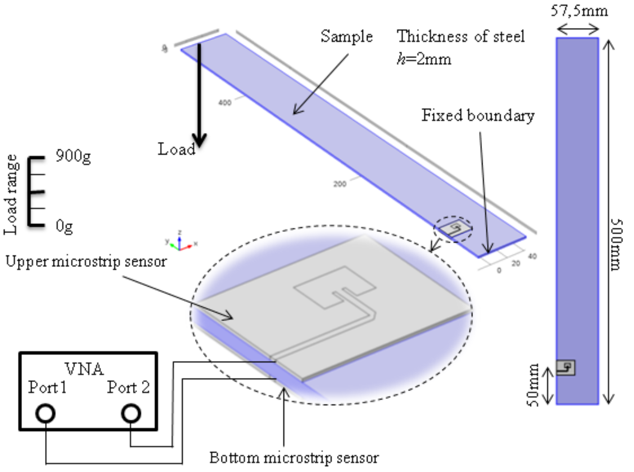

Fig. 3. Scheme of experiment and dimensions of sample.

Parameter name	Parameter value
Young's modulus *E*	200 GPa
Yield point	235 MPa
Limit state	380 MPa
Bending Limit state	145 MPa
Density	7850 kg/m^3

Tab. 2. Mechanical properties of St3s (S235JRG2) steel according to PN-88 H-84020 (EN10025).

of displacement u_y, because it only shows the summary of displacement. Therefore, the position of sensors was determined by the local change of displacement. The highest displacement derivative values are from 10 to 70 mm as shown in Fig. 5. Thus, 50 mm distance from a fixed boundary was selected.

The microstrip sensors were produced by the photolithography process. Two identical transducers were created. The manufactured sensor is presented in Fig. 6. Antenna sensors have been made on the double-side polymer laminate of thickness of 0.5 mm, relative permittivity of 4.5. The patch, microstrip line and ground are made of copper (layer thickness of 35 μm). The antenna is probe fed with a 50 Ω SMA connectors.

The microstrip antenna sensors were fixed using cyanoacrylate glue on the top and bottom surface of the sample as shown in Fig. 3 and 7. This adhesive connection allows transmission of sample deformation to microstrip sensors. Measurements were carried out using Rohde&Schwarz ZVB20 vector network analyzer in 10 MHz–20 GHz frequency range with step of 2 MHz. The photo of the measuring system is shown in Fig. 7. The sample was attached to the static holding element and the other side was loaded with different weights in order to introduce different deformation. Change of utilized load caused damped oscillations of the sample. For this reason the S_{11} coefficient was measured 60 seconds after load addition.

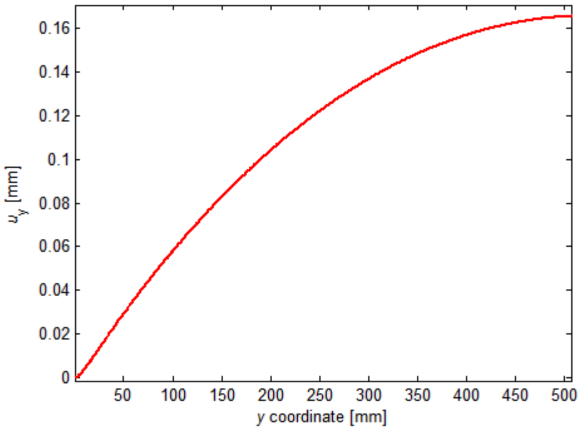

Fig. 4. Displacement u_y (y component) along the beam sample.

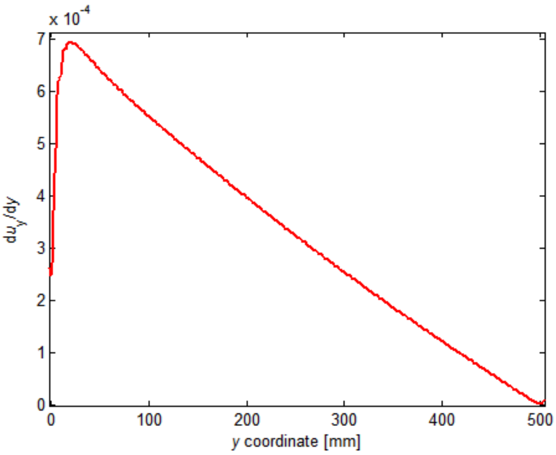

Fig. 5. Derivative of u_y along of the beam sample (y component).

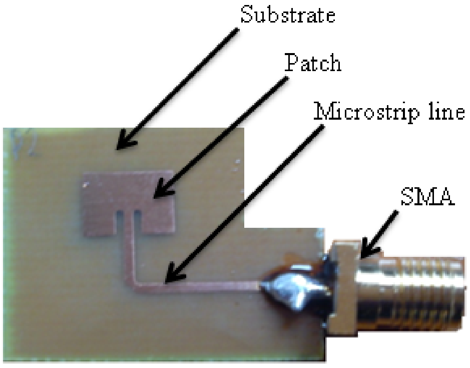

Fig. 6. Photo of the manufactured microstrip SHM sensor [20].

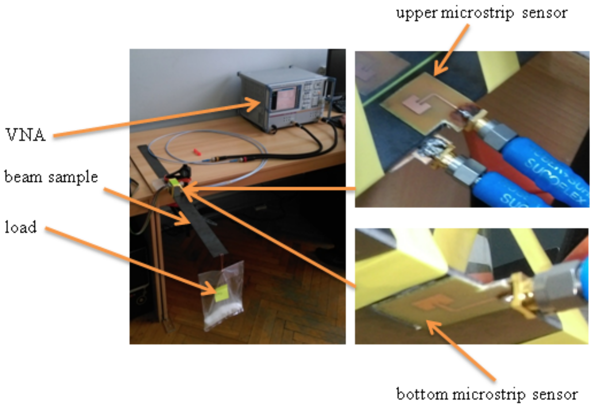

Fig. 7. Photo of the measuring system.

4. Results of Experiments

4.1 Numerical Analysis

Numerical and experimental analyses were carried out. In order to evaluate the proposed sensor FEM (Finite Element Method) numerical model was developed in Comsol Multiphysics environment. Solid mechanics module was used in order to obtain deformation of steel sample and sensor geometry [33]. Afterwards, the RF module enabled calculation of reflection coefficient for the deformed sensor [34].

The numerical model with the mechanical scheme and the calculated total displacement for maximum load (within

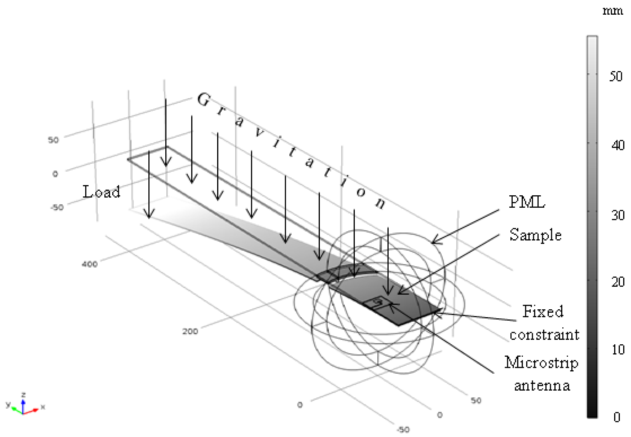

Fig. 8. FEM numerical model of the experimental setup with calculated total displacement for maximum load (grey level) [20].

elastic range of the material stress-strain relationship) are presented in Fig. 8. The sample is affected by both the force of gravity and the force attached to its end.

The patch sensors are in the center of two concentric spheres. The inner sphere acts as an environment of the sensor – it enables the propagation of electromagnetic waves. The outer part of the bigger sphere (outside the inner sphere) enables absorption of electromagnetic waves generated by the transducers (Perfectly Matched Layers, PML). The computational mesh has 235 265 tetrahedral elements. The reflection coefficient S_{11} represents the power reflected from the antenna related to the incident one. The coefficient is determined in frequency domain. The calculated frequency response is presented in Fig. 9, this is a typical resonant characteristics for radiating microstrip structures. The frequency characteristics of S_{11} parameter was calculated while the sample was not affected by any force. The value of f_r without any load was designated. The simulation was carried out in 4–15 GHz frequency range with step of 1 MHz. This step length ensured sufficient accuracy of f_r determination. The electric field distribution for resonant frequency is illustrated in Fig. 10.

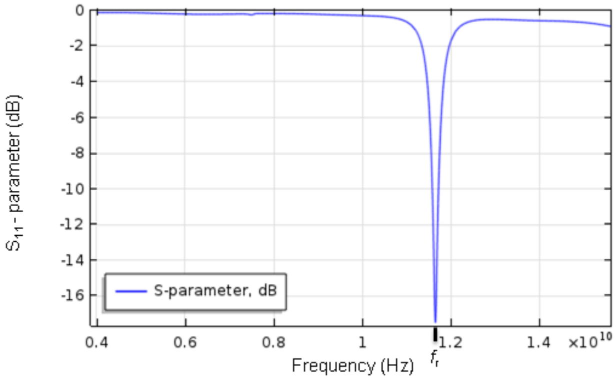

Fig. 9. Reflection coefficient for utilized sensors [20].

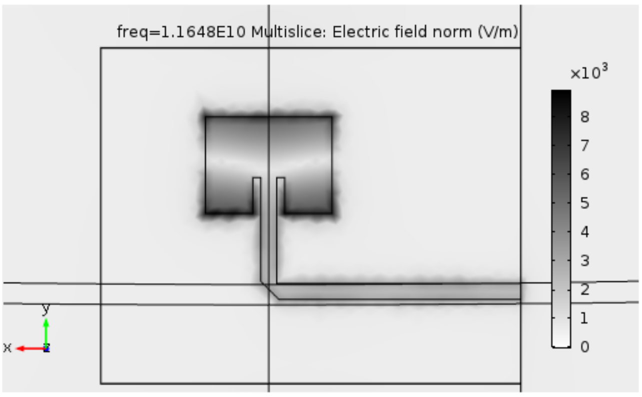

Fig. 10. Electric field for resonant frequency.

In the considered setup the deformation along the sample is dominant, thus it is assumed, that it is measured by the change of the patch length ΔL. The relationship between the change of the patch length ΔL and the mass of the load m is presented in Fig. 11. If it is assumed that only the change in the patch dimensions influences resonant frequency (influence of curvature is not considered), the f_r value for upper sensor should be decreased, whereas for the bottom patch sensor ought to be increased with the rise of load. It is caused by the change of the microstrip sensor effective length. The patch of the upper sensor is lengthened and the patch of the bottom sensor is shortened. The results for upper microstrip sensor were predictable as shown in Fig. 12 and 14. The resonant frequency of this sensor was decreased while increasing the load (longer patch causes lower f_r). In case of the bottom sensor it is different (presented in Fig. 13 and 14). For small elongations the resonant frequency of this transducer was increased, but subsequently it was decreased while increasing the load. This effect will be analyzed more detailed later in this section. In Fig. 14 the shifts of the resonant frequency in function of the patch length change for both sensors were presented. Nonzero value of Δf_r and ΔL (Fig. 11) in case of $m = 0$ g is caused by the force of gravity. Cubic polynomial approximation was used to improve the accuracy of the resonant frequency evaluation.

Numerical analysis exhibited that the shift of the resonant frequency was not only depended on the length of the patch. Thus, the curvature effect will be investigated. In order to determine the influence of this effect two numerical models: convex and concave (illustrated in Fig. 15 and 16) were considered. The influence of radius r on the resonant frequency was studied by these numerical models. During the calculations the length of r was changed, while the dimensions of patch, microstrip line, width and length of substrate curve were constant.

The curvature effect for the upper sensor was studied by the convex model and for the bottom sensor it was investigated by the concave model. The value of r decreased with raising load. The curvature effect has opposite influence on resonant frequency towards changing of patch length, but in case of the upper sensor this effect is less significant (comes out for smaller radius) than in case of the bottom sensor (Fig. 17). For the bottom sensor, a reduction of the patch length caused the growth of f_r, on the other hand the curvature effect causes decrease of resonant frequency. In case of the upper sensor, the increase of the patch length causes decreasing f_r, whereas the curvature effect entails increasing of resonant frequency with raising load.

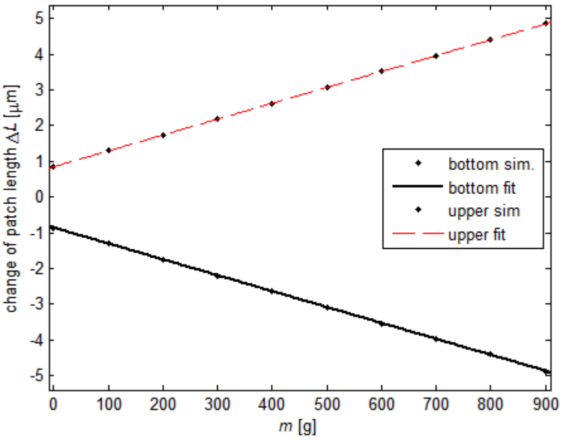

Fig. 11. Relationships between the mass of the load and the change of the patch length derived by the simulation model.

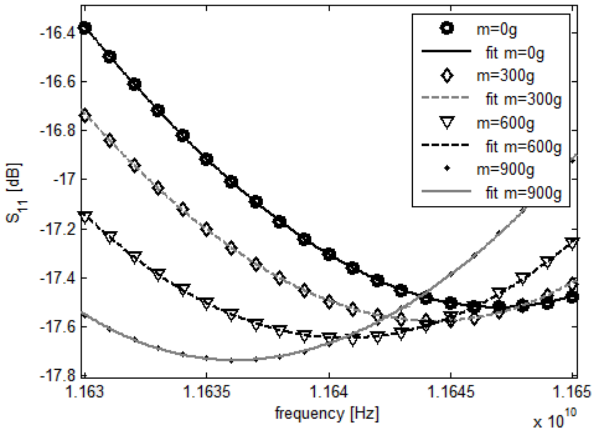

Fig. 12. Reflection coefficient S_{11} of the upper sensor for different loads [20].

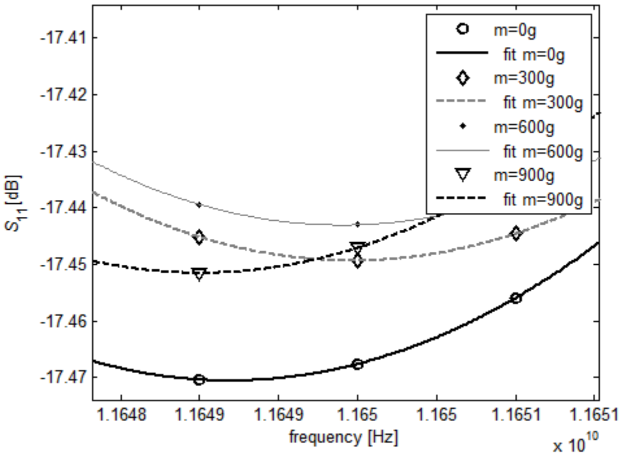

Fig. 13. Reflection coefficient S_{11} of the bottom sensor for different loads.

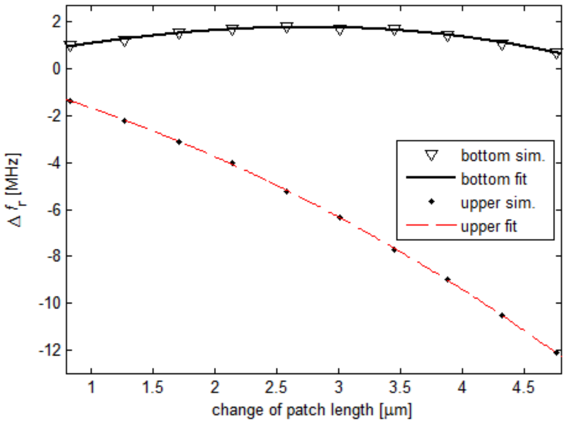

Fig. 14. Deformation evaluation by both sensors (numerical analysis).

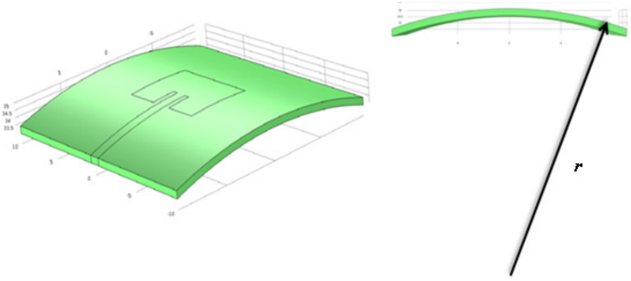

Fig. 15. Convex model.

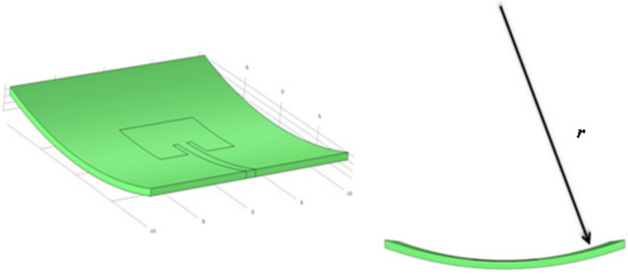

Fig. 16. Concave model.

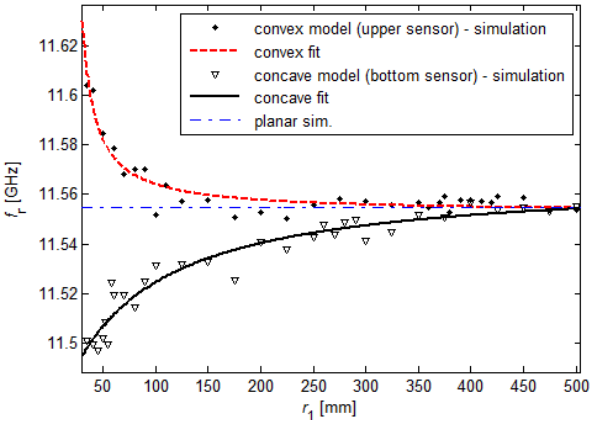

Fig. 17. Dependence of the curvature radius and resonant frequency.

4.2 Results of Experimental Analysis

In order to verify the correctness of FEM simulations, experimental analysis was carried out. The results of measurements are shown in Fig. 18. The resonant frequency of the upper sensor was decreased with the increasing load. This shift was caused by the increase of the effective length of the patch. The influence of the curvature effect for this microstrip sensor was relatively small. In the case of the bottom microstrip sensor, the impact of this phenomenon on the resonant frequency was higher than for the upper patch sensor, so that utilization of the convex model of transducer is recommended.

5. Conclusions

In this article the deformation measurement in bended steel element by rectangular microstrip sensor was investigated. The proposed sensors were adhesively connected to both sides of a sample, thus during the bending process the sensor geometry became non-planar. For the designed sensor the influence of the curvature effect on resonant frequency was investigated. Furthermore, it should be pointed that the impact of the change of the patch length in connection with the curvature effect was considered, which has not been presented in literature yet. A good agreement of simulated and measured results was obtained. Comparisons of the results are presented in Fig. 19. However, this type of sensor should be used carefully for deformation measurements in bending elements, because the curvature effect has opposite impact on the resonant frequency than changing the length of the patch. Therefore, the place of attaching the sensor ought to be well selected.

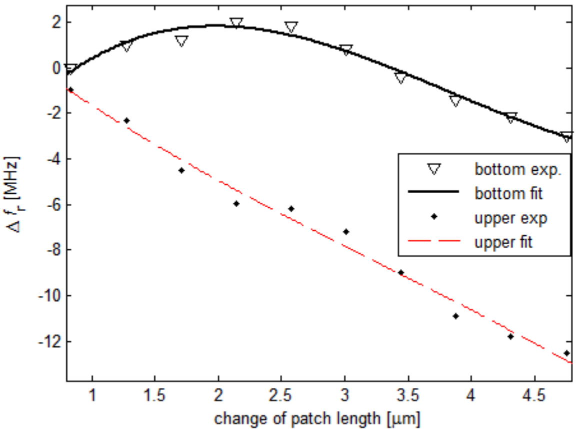

Fig. 18. Deformation evaluation by both sensors (experimental analysis).

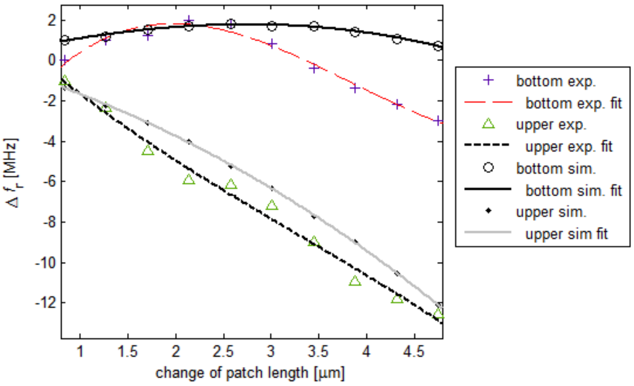

Fig. 19. Comparison of simulation and measurement results.

Microstrip SHM sensors could be further developed for wireless Structural Health Monitoring application. It may increase the area of SHM techniques application and thereby increase the safety of structures. In the further work the directional characteristics of the rectangular microstrip sensor will be determined and the influence of the curvature effect for other directions will be studied. One of the ideas to minimize the influence of the curvature effect is application of tunable antennas [35–37].

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